Nuclear suppression at RHIC and LHC in Glauber-Gribov approach

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Abstract. The approach to problem of nuclear shadowing based on Gribov Reggeon calculus is presented. Here the total cross section of hA interaction is found in a parameter-free description, employing the new data on the gluon density of the Pomeron, measured with high precision at HERA, as input. The model is then applied for calculation of J/ψ production in dAu collisions at top RHIC energy. It is shown that the theoretical estimates are in a very good agreement with the PHENIX data, and further predictions for the J/ψ suppression in pPb collisions at coming soon LHC are made.

1. Introduction

One of the ultimate goals of the heavy-ion collision programme at ultra-relativistic energies is the search for fingerprints of a new state of matter, the so-called quark-gluon plasma (QGP). Since up to now no signals are observed which can be unambiguously attributed to the QGP formation in hadron−hadron (hh) or hadron−nucleus (hA) interactions, such processes are used as reference ones for comparison with the nuclear ($A+A$) collisions. On the other hand, even the physics of (hA) interactions is not completely understood yet. For instance, experimentalists found a substantial decrease of the nuclear absorption in J/ψ production in deuteron−gold (dAu) collisions at top RHIC energy, $\sqrt{s} = 200$ AGeV, in comparison with proton−lead interactions at SPS, $E_{lab} = 158$ AGeV [1]. Here the dynamics of the collision is obviously changing with rising bombarding energy, and new effects come into play. To study these processes we employ the Gribov Reggeon theory (GRT) [2], which enables one to take into consideration both soft and hard processes.

Figure 1. (a) Planar and (b) non-planar diagrams of hA scattering.

At low incident energies the multiple scattering of incoming hadron on nuclei is described by the planar diagrams shown in Fig. 1(a). It appears that in this energy range the total cross section of the process, calculated within the GRT, is equal to that given by the probabilistic Glauber model [3], which takes into account successive elastic rescatterings of the incoming hadron on the nucleons of the target. Note, that the multiple scattering in the Glauber model leads to reduction of the total cross section. The situation changes dramatically at energies higher than a certain critical energy E_{crit} [2]. Above E_{crit} the typical length of hadronic fluctuations becomes comparable or even exceeds the nuclear radius, thus leading to the coherent interaction of hadron constituents with several nucleons. The main contribution to the total cross section comes here from the non-planar diagrams, depicted in Fig. 1(b), while the contribution from the planar diagrams drops with rising energy inversely proportional to E. Since the interactions with different nucleons of the target nucleus occur almost simultaneously, the space-time analogy to the Glauber rescattering series is lost. The diffractive intermediate states should be taken into account [2], and the total cross section is further reduced. The phenomenon is colloquially known as nuclear shadowing. It can be decomposed onto the quark shadowing and the gluon shadowing; the latter provides largest theoretical uncertainties.

2. Inelastic shadowing in Gribov model

Below we will follow the procedure formulated in details in [4–6]. The hA cross section is expanded in infinite series containing the contributions from $1, 2 \ldots$ scatterings

$$\sigma_{hA}^{(tot)} = \sigma_{hA}^{(1)} + \sigma_{hA}^{(2)} + \ldots \, , \tag{1}$$

where the first term represents the sum of independent interactions and the subsequent terms describe multiple inelastic interactions, respectively, of the incoming probe with the nucleons in the target nucleus. The contribution from the second term, $\sigma_{hN}^{(2)}$, arises from the cut contribution of the double rescattering diagrams. It appears that this term is identical to minus the contribution from the diffractive cut, thus linking the nuclear shadowing to the diffractive deep inelastic scattering (DDIS). The standard variables for the description of the DDIS are Q^2, x, M^2 and t, or $x_{I\!P}$; they are depicted in Fig. 2. The variable $\beta = \frac{Q^2}{Q^2+M^2} = x/x_{I\!P}$ plays the same role for the Pomeron as the Bjorken variable, x, for the nucleon. We have a reduction of the total hA cross section by a term

$$\sigma_{hA}^{(2)} = -4\pi A(A-1) \times \tag{2}$$
$$\int \mathrm{d}^2 b\, T_A^2(b) \int_{M_{min}^2}^{M_{max}^2} \mathrm{d}M^2 \left[\frac{\mathrm{d}\sigma_{hN}^{\mathcal{D}}(Q^2, x_{I\!P}, \beta)}{\mathrm{d}M^2\, \mathrm{d}t} \right]_{t=0} F_A^2(t_{min}) \, ,$$

where

$$T_A(b) = \int_{-\infty}^{+\infty} \mathrm{d}z\, \rho_A(\boldsymbol{b}, z)$$

is the nuclear normalized density profile, $\int \mathrm{d}^2 b\, T_A(b) = 1$. The form factor F_A is expressed as

$$F_A(t_{min}) = \int \mathrm{d}^2 b\, J_0(\sqrt{-t_{min}}b)\, T_A(b) \, , \tag{3}$$

with $t_{min} = -m_N^2 x_{I\!P}^2$, and $J_0(x)$ denoting the Bessel function of the first kind. Although Eq. (2) is an identity for nuclear densities which depend separately on $\boldsymbol{b}$ and

z, we have checked [7] that calculations with an exact expression lead to negligible corrections. Since Eq. (2) is obtained under very general assumption, i.e. analyticity and unitarity, it can be applied for arbitrary values of Q^2 provided x is very small. For a deuteron, the double rescattering contribution has the following form

$$\sigma_{hd}^{(2)} = -2 \int_{-\infty}^{t_{min}} dt \int_{M^2_{min}}^{M^2_{max}} dM^2 \frac{d\sigma_{hN}^{\mathcal{D}}}{dM^2 dt} F_D(t) , \tag{4}$$

where the deuteron form factor is roughly approximated as $F_D(t) = \exp(at)$, with $a = 40$ GeV^{-2} [4].
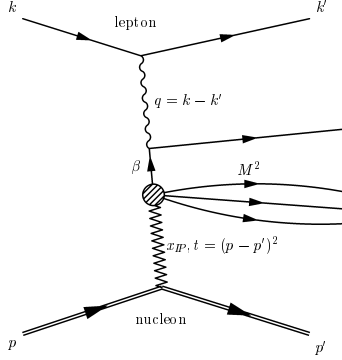

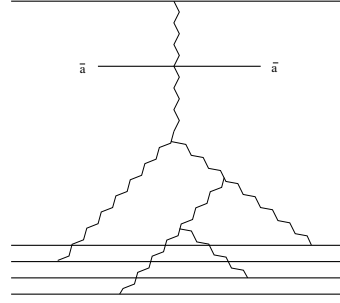**Figure 2.** DDIS kinematical variables in the infinite momentum frame.

Figure 3. Enhanced diagram for the inclusive production of particle a.

The integration limit M^2_{min} corresponds to the minimal mass of the diffractively produced hadronic system, $M^2_{min} = 4m^2_\pi = 0.08 \text{GeV}^2$, and M^2_{max} is chosen from the condition: $x_{I\!P} \leq 0.1$. It guarantees [8] the disappearance of nuclear shadowing at $x \sim 0.1$ in accord with experimental data. Coherence effects are taken into account via $F_A(t_{min})$, which equals to 1 at $x \to 0$ and decreases with increasing x due to the loss of coherence for $x > x_{crit} \sim (m_N R_A)^{-1}$. In the calculations a 3-parameter Woods-Saxon nuclear density profile with parameters from [9] has been used.

For higher order rescatterings we use the Schwimmer unitarization [10] for the total hA cross section which is obtained from a summation of fan-diagrams with triple-Pomeron interactions shown in Fig. 3. As was checked in [4], this method provides results very close to other reasonable models, such as the quasi-eikonal model. The total cross section is then

$$\sigma_{hA}^{Sch} = \sigma_{hN} \int d^2b \, \frac{A \, T_A(b)}{1 + (A-1)f(x,Q^2)T_A(b)} . \tag{5}$$

Thus the total hA cross section can be calculated within the Glauber-Gribov model in a parameter-free way provided the total hN cross section and the differential cross section for diffractive production are known. To determine the shadowing for quarks and antiquarks one has to insert in Eq. (5)

$$f(x,Q^2) = 4\pi \int_x^{x_{I\!P}^{max}} dx_{I\!P} \, B(x_{I\!P}) \frac{F_{2\mathcal{D}}^{(3)}(x_{I\!P},Q^2,\beta)}{F_2(x,Q^2)} F_A^2(t_{min.}) . \tag{6}$$

Here $F_2(x,Q^2)$ is the structure function for a nucleon, $F_{2\mathcal{D}}^{(3)}(x_{I\!P},Q^2,\beta)$ is the t-integrated diffractive structure function of the nucleon, $B(x_{I\!P}) = B_0 + \alpha'_{I\!P} \ln \frac{1}{x_{I\!P}}$,

$\alpha'_{I\!P}$ is the slope of the Pomeron trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}t$ (see [11]), and $F_A(t_{min})$ is given by Eq. (3). Note, that the real part of the diffractive amplitude in Eqs. (2),(5),(6) is neglected. Similar expressions are valid for the gluon shadowing with substitutions $F_{2\mathcal{D}}^{(3)}\left(x_{I\!P}, Q^2, \beta\right) \rightarrow \beta g^{\mathcal{D}}(\beta, Q^2)$, $F_2\left(x, Q^2\right) \rightarrow xg\left(x, Q^2\right)$, indicating gluon distributions in DDIS and in the proton, respectively. Gluon distribution of the nucleon is taken from CTEQ6M parameterization [12]. We take information on the diffractive gluon distribution and Pomeron parameters from recent HERA measurements [11]. Further details of the developed approach can be found in [4–6].

3. Nuclear effects in heavy quarkonium production

As was already mentioned in Introduction, the substantial decrease of the nuclear absorption in J/ψ production, observed by PHENIX collaboration in dAu collisions at RHIC [1], has attracted a lot of attention. Many models predict that absorptive effects would increase or, at least, remain constant with rising collision energy [14]. However, such a behavior of absorptive cross section allows for a natural explanation in the framework of Gribov theory. We argue that the apparent observation of the reduction of $\sigma_{abs}^{J/\psi}$ can be interpreted as a signal of the onset of coherent scattering for heavy-state production.

The reason is as follows [15]. At very high energies Abramovsky-Gribov-Kancheli (AGK) cutting rules [16] lead to a cancellation of the Glauber-type diagrams in the central rapidity region, i. e. for $x_F \approx 0$, and only enhanced diagrams (see Fig. 3) [17] give non-zero contributions. But both at non-zero x_F and at lower energies the AGK cancellation is not valid due to energy-momentum conservation [18]. This leads to an increase of effective "absorption" with rising x_F. The energy dependence of AGK violation is different for light- and heavy-state production because of the mass difference. For heavy quark states the mass $M_{Q\bar{Q}}$ of the heavy system introduces a new scale

$$s_M = \frac{M_{Q\bar{Q}}^2}{x_+} \frac{R_A m_N}{\sqrt{3}} , \tag{7}$$

where $x_+ = \frac{1}{2}(\sqrt{x_F^2 + 4M_{Q\bar{Q}}^2/s} + x_F)$ is the longitudinal momentum fraction of the heavy system. It was shown [19] that AGK cutting rules are changed at $s = s_M$. At energies below s_M longitudinally ordered rescatterings of the heavy system take place. At $s > s_M$ the heavy state in the projectile scatters coherently off the nucleons of a nucleus, and the conventional treatment of nuclear absorption is not adequate. In the central rapidity region the values of s_M for J/ψ are within the RHIC energy range. Accordingly, the effects of shadowing of nuclear partons become important and can be calculated using Gribov theory of nuclear structure functions in the region of $x_2 < (m_N R_A)^{-1}$. Based on the above discussion we calculate the suppression of J/ψ production in the central rapidity region in pA collisions at $\sqrt{s} = 200$ GeV taking into account shadowing effects [20]. A similar approach, albeit with a simpler parameterization of nuclear shadowing, has also been considered in [21].

PHENIX collaboration has measured the nuclear modification factor (NMF) of J/ψ production in dAu collisions at RHIC as a function of centrality [1]. The centrality dependent NMF is defined as

$$R_{dAu}\left(\langle N_{coll}\rangle\right) = \frac{N_{inv}^{dAu}\left(\langle N_{coll}\rangle\right)}{\langle N_{coll}\rangle \times N_{pp}^{inv}} , \tag{8}$$

where the average number of nucleon-nucleon collisions $\langle N_{coll} \rangle$ is obtained from the Glauber model for a given centrality.
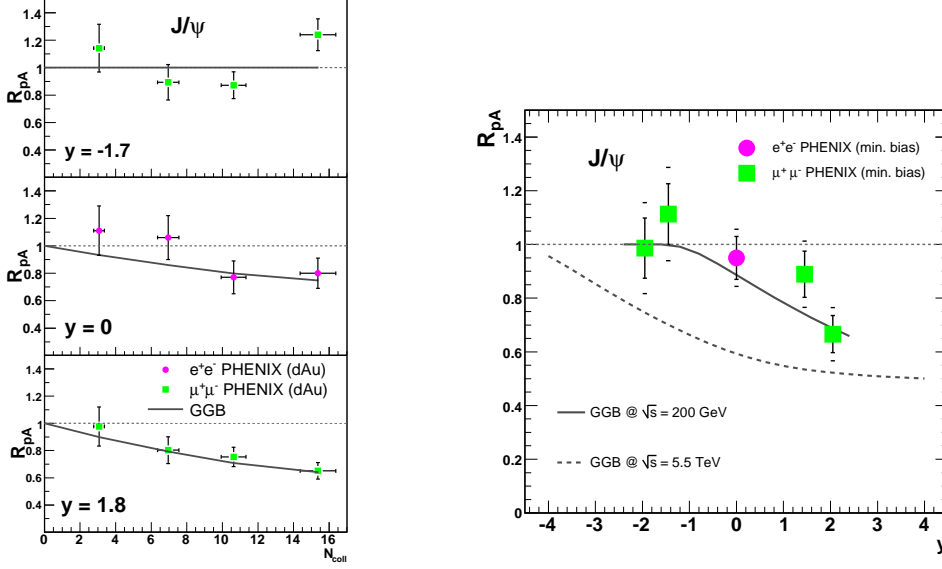

Figure 4. (a) Centrality and (b) rapidity dependence of the nuclear modification factor $R_{pA}^{J/\psi}$ in $d\ Au$ and $p\ Pb$ collisions at top RHIC and LHC energies. Data are taken from [1].

In the model considered here the suppression factor is given by

$$R_A(b, x, Q^2) \;=\; \frac{A T_A(b)}{1 \,+\, (A-1)f(x, Q^2)T_A(b)} \;, \tag{9}$$

where $f(x, Q^2)$ is given by Eq. (6). The summation of planar and non-planar diagrams provides us the following expression for the ratio of inclusive spectra in dA and pp collisions

$$E\frac{\mathrm{d}^3\sigma_{dAu}}{\mathrm{d}^3 p}(b)/E\frac{\mathrm{d}^3\sigma_{pp}}{\mathrm{d}^3 p} \;=\; \int \mathrm{d}^2 s R_d(\mathbf{b}, x_p)R_{Au}(\mathbf{s}-\mathbf{b}, x_t) \tag{10}$$

where $x_{p(t)} = m_\perp \exp(\pm y)/\sqrt{s}$ (we take $m_\perp = Q$ and $Q = 4$ GeV). This is what we compare to the nuclear modification factor presented by Eq. (8).

The results of calculations are shown in Fig. 4(a) for the NMF at backward, mid- and forward rapidity. Since the model of gluon shadowing does not include anti-shadowing effects, the result is quite trivial in the backward hemisphere, although not inconsistent with the data. Anti-shadowing is assumed to be a 10% effect. At rapidity $y = 0$ and $y = 1.8$ the consistency with experimental data is quite good. Within other parameterizations of nuclear shadowing, the data has been shown to be consistent with an absorptive cross section of 1-2 mb [1], which is smaller than at lower energies. Whereas the absorptive effects were predicted to increase with energy [13], our model provides a unique explanation of the competing effects of shadowing and absorption at high energies. Description of nuclear modification factor R_{dAu} for minimum bias dAu collisions at RHIC [1] and predictions for pPb collisions at LHC are presented

in Fig. 4(b). While being accounted for about 10% drop of the NMF at $y = 0$ at RHIC, gluon shadowing at LHC should reduce the NMF of J/ψ to $R_{pPb}^{J/\psi} \simeq 0.6$ at mid-rapidity and to $R_{pPb}^{J/\psi} \simeq 0.5$ at forward rapidities for minimum bias events.

4. Conclusions

We have discussed the vanishing of nuclear absorption and the appearance of shadowing in the context of J/ψ production at RHIC and LHC energies. Within the Gribov model this is related to a change of the space-time dynamics of the collision, going from incoherent, longitudinally ordered scattering at low energies to coherent scattering at higher energies. Within the same model we calculated gluon shadowing using recent measurements of gluon diffractive parton density at HERA as input.

A comparison to experimental data from RHIC at mid-rapidity and away from it shows good agreement. We predict a stronger shadowing effect at LHC. Gluon shadowing is also a crucial input for the correct treatment of final-state effects in nucleus-nucleus collisions.

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